



Rules for Optical Metrology

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Rules for Optical Metrology

Based on 30 years of optical testing experience, a lot of mistakes, a lot of learning and a lot of experience,

I have defined seven guiding principles for optical testing – regardless of how small or how large the optical testing or metrology task

GUIDING PRINCIPLES

1. Fully Understand the Task
2. Develop an Error Budget
3. Continuous Metrology Coverage
4. Know where you are
5. ‘Test like you fly’
6. Independent Cross-Checks
7. Understand All Anomalies

These rules have been applied with great success to the in-process optical testing and final specification compliance testing of the JWST mirrors.



Rule #1: Fully Understand the Task

Make sure that you fully understand your task:

- who is your customer;
- what parameters do you need to quantify;
- to what level of uncertainty you must know their value; and
- who is your manufacturing interface?

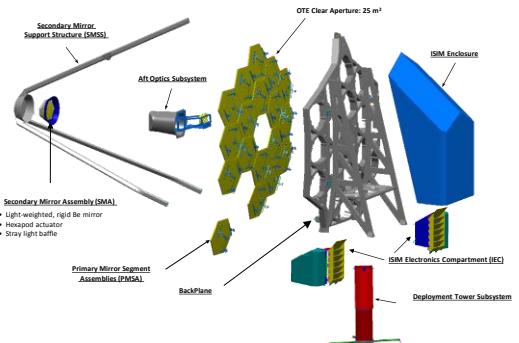
Before accepting any testing task, study your customer’s requirements and understand how they relate to the final system application.

Then summarize all requirements into a simple table which can be shared with your customer and your manufacturing methods engineer.

Make sure that your customer agrees that what you will quantify satisfies their requirements and the manufacturing methods engineer agrees that they can make the part based upon the data you will be providing.



JWST is Customer making Segmented PM



JWST Optical Testing Needs

The principle JWST optical testing needs include:

Optical Component Assemblies

Primary Mirror Segment Assembly (PMSA)	18 + 3 spares
Secondary Mirror Assembly (SMA)	1 + 1 spare
Tertiary Mirror Assembly (TMA)	1

Observatory Elements

Primary Mirror Assembly (PMA)	
Optical Telescope Element (OTE)	

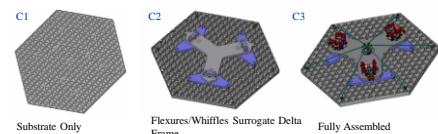
Additionally, there are multiple other optics such as the fine steering mirror and various instrument optical components.



Optical Component Configurations

There are 3 mirror configuration ‘states’:

- Configuration 1 = Substrate Only
- Configuration 2 = Flight Flexures & Whiffle and Surrogate Delta Frame
- Configuration 3 = Flight





JWST Optical Component Specifications

All Components have Cryogenic Performance Specifications

Since components are fabricated at Ambient it is necessary to Cryo-Null Figure, i.e. compensate for ambient to cryo changes

All Components have:

- an Initial Requirement which must be met before Cryo-Testing
- a Final Post Cryo-Null Figuring Requirement, and
- a Final Cryogenic Performance Requirement



Segment Fabrication Requirements & Tolerances

Parameter	Specification	Tolerance	Units	Comments
Requirements for initial figuring				
Clear Aperture (Edge Specification)	1.4776 mm (5) ²	Min 80-50	mm ²	Maximum *Different for 3 segments
Scratch-Dig	0.09666	+/- 0.0005	mrad	
Conic Constant	-0.99666	+/- 0.0005	mrad	
Radius of Curvature	15899.915	+/- 1	mm	
Prescription Alignment Error				
Decenter	*	≤ 0.35	mm	*Different for 3 segments
Clocking	0	≤ 0.35	mrad	
Piston	N/A			Measure only, no requirement
Tilt	N/A			Measure only, no requirement
Total Surface Figure Error:				
Low/Mid Frequency (~222 mm/cycle)	150	Maximum	nm rms	
High Frequency (222 to 0.08mm/cycle)	20	Maximum	nm rms	
Slope Error	25	Maximum	μrad	
Requirements for cryo-null figuring				
Clear Aperture (based on Edge Specification)	1.4776 mm (5) ²	Minimum	mm ²	*Different for 3 segments
Scratch-Dig	0.09666	+/- 0.0005	mrad	
Conic Constant	-0.99666	+/- 0.0005	mrad	
Radius of Curvature	*	+/- 0.10	mm	*Radius value supplied
Prescription Alignment Error				
Decenter	*	≤ 0.35	mm	* Decenter value supplied
Clocking	0	≤ 0.35	mrad	
Piston	N/A			Measure only, no requirement
Tilt	N/A			Measure only, no requirement
Total Surface Figure Error:				
Low/Mid Frequency (~222 mm/cycle)	20	Maximum	nm rms	Relative to cryo-target map
High Frequency (222 to 0.08mm/cycle)	7	Maximum	nm rms	Relative to cryo-target map
PSD Spike Requirement			Spike Limit	
Surface Roughness	4	Maximum	nm rms	



Metrology Plan for Each Requirement

Parameter	Spec	Tol	Units	Verification	Validation
Clear Aperture (Edge Specification)	1.4776 mm (5) ²	mm ²	mm	Measure edges at ambient using Tinsley HS Interferometer	Measure area at cryo using XRCF CoC Interferometer
Scratch-Dig	80-50 Max		mm	Ambient Visual Inspection	Independent Visual
Conic Constant	-0.99666 +/- 0.0005			Measured at cryo and defined by null geometry for XRCF GHG CoC test	Ambient test at Tinsley, compare GHG CoC test with auto-collimation test
Radius of Curvature	*	+/- 0.15	mm	Set at XRCF using ADM	ROCO Comparison
Prescription Alignment Error					
Decenter	*	≤ 0.35	mm	Cryogenic test at XRCF, defined by relative misalignment error relative to GHG CoC test and fiducial alignment	Ambient test at Tinsley, compare GHG CoC test with auto-collimation test
Clocking	0	≤ 0.35	mrad		
Piston	N/A			Ambient CMM measurement at AXYS	Ambient CMM measurement at Tinsley
Tilt	N/A				
Total Surface Figure Error:					
Low/Mid Frequency	20	Max	nm rms	Cryo-Test at XRCF	Cryo-Test at ISC
High Frequency	7	Max	nm rms		
Surface Roughness	4	Max	nm rms	Ambient Chapman measurement at Tinsley	NONE



Lesson Learned Example

A simple example of how not ‘fully understanding the task’ causes trouble is Zernike polynomial coefficients.

Optical designers use Zernike coefficients to specify components and metrologists use Zernike coefficients to describe surface shape. But, which Zernike coefficients? Also, PV or RMS?

Table 1. Zernike Polynomial Coefficient Index (first 8 coefficients only)						
Description	Polynomial	ISO	FRINGE	Born & Wolfe	Kodak	RMS to PV Ratio
Piston	1	0	1	1	0	1
X-Tilt	$r \cos\theta$	1	2	2	1	
Y-Tilt	$r \sin\theta$	1	3	3	1	10
Power	$2r^2 - 1$	3	4	5	3	
X-Astigmatism	$r^2 \cos 2\theta$	4	5	4	4	4
Y-Astigmatism	$r^2 \sin 2\theta$	5	6	5	6	5
X-Coma	$(3r^2 - 2)r \cos\theta$	6	7	8	7	6
Y-Coma	$(3r^2 - 2)r \sin\theta$	7	8	9	8	7
Spherical	$6r^4 - 6r^2 + 1$	8	9	13	10	13

Design software typically use B&W while Interferometer software typically use Fringe. Orders are different.



Lesson Learned Example

Also, some designers and fabricators use PV Zernike Coefficients and some use RMS.

Optical designers use Zernike coefficients to specify components and metrologists use Zernike coefficients to describe surface shape. But, which Zernike coefficients? Also, PV or RMS?



Rule #2: Develop an Error Budget

Develop an error budget for every specification & tolerance.

Error budget predicts test accuracy and reproducibility (not repeatability) of the metrology tools.

Reproducibility is the ability of ‘independent’ measurement executions to achieve the same answer, e.g. take down and re-set a test.

All elements of error budget must be certified by absolute calibration and verified by independent test.

An error budget has multiple functions.

Convinces your customer that you can actually measure the required parameters to the required tolerances;
Defines which test conditions have the greatest impact on test uncertainty;
Provides a tool for monitoring the test process.

If the variability in the test data exceeds the error budget prediction, then you must stop and understand why.

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Description	Polynomial	ISO	FRINGE	Born & Wolfe	Kodak	RMS to PV Ratio
Piston	1	0	1	1	0	1
X-Tilt	$r \cos\theta$	1	2	2	1	
Y-Tilt	$r \sin\theta$	1	3	3	1	10
Power	$2r^2 - 1$	3	4	5	3	
X-Astigmatism	$r^2 \cos 2\theta$	4	5	4	4	1(Sqr)3
Y-Astigmatism	$r^2 \sin 2\theta$	5	6	5	6	1(Sqr)6
X-Coma	$(3r^2 - 2)r \cos\theta$	6	7	8	6	1(Sqr)8
Y-Coma	$(3r^2 - 2)r \sin\theta$	7	8	9	7	1(Sqr)8
Spherical	$6r^4 - 6r^2 + 1$	8	9	13	10	1(Sqr)5



Error Budget Contingency

An Error Budget **MUST** have Contingency Reserve.

No matter how much one thinks about every potential contingency risk or how careful one executes, errors happen.

Three examples of mirrors fabricated according to an error budget – which were in fact better than the error budget until an error occurred. Because of Reserve, they all met their final requirement specification.

On Spitzer, the assembled telescope was well below its requirement until the shake test. A bolt hole which was not deep enough introduced forces which bent the Primary Mirror (by approx 1/3rd of its requirement). But, the total system still met spec.

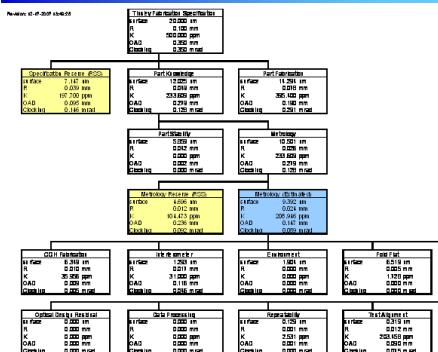
On JWST, as the primary mirror segment fabrication process improved, the segments were greatly below their requirement. But, an incorrect calibration file was used on two PMSAs resulting in residual excess power (of approx 1/3rd of its figure requirement). But, the primary mirror still met spec.

On Spitzer, the secondary mirror's ambient surface figure error was well below its requirement. But, metal tape used to attach the thermal couples to the secondary mirror during its cryo test introduced a residual error into the cryo-hit map (of approx 1/3rd of its figure requirement). But, the primary mirror still met spec.

A good value for Error Budget Reserve is 33% of the Requirement.

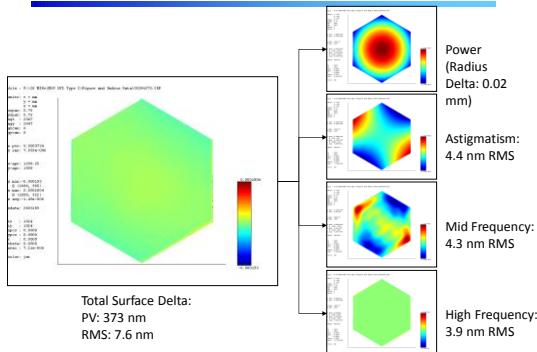


JWST PMSA Error Budget

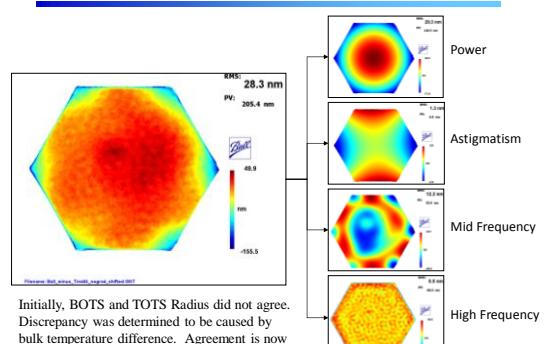


Tinsley Test Reproducibility

(OTS-1 Test #1 vs. Test #2) VC6GA294-VC6HA270

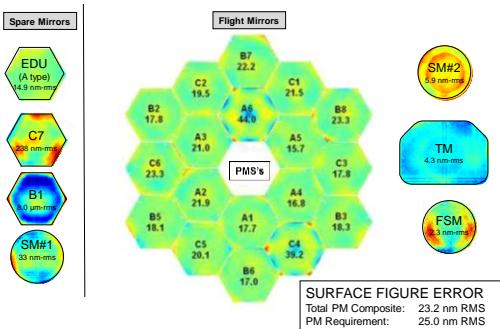


BATC to Tinsley Initial Comparison too large



Mirror Fabrication Status

ALL DONE & DELIVERED



Develop an Error Budget

To correct way to develop an error budget is to perform a propagation of error analysis.

Start with the equation which defines how the requirement is calculated from the measured parameters.

Propagation of error connects the uncertainty of the calculated parameter to the uncertainty of the measured quantities.

$$\sigma_R = \sqrt{\left(\frac{\delta f(a, b, c)}{\delta a}\right)^2 \sigma_a^2 + \left(\frac{\delta f(a, b, c)}{\delta b}\right)^2 \sigma_b^2 + \left(\frac{\delta f(a, b, c)}{\delta c}\right)^2 \sigma_c^2}$$



Continuous Metrology Coverage

Ordinarily, optical fabricators try to move directly from CMM to optical test during fine grinding. But, given the size of JWST PMSAs and the mid-spatial frequency specification, this was not possible.

Bridge data was provided by a Wavefront Sciences Scanning Shack Hartmann Sensor (SSHS).

Its infrared wavelength allowed it to test surfaces in a fine grind state. And, its large dynamic range (0 to 4.6 mrad surface slope), allowed it to measure surfaces which were outside the interferometer's capture range.



Wavefront Sciences Scanning Shack-Hartmann

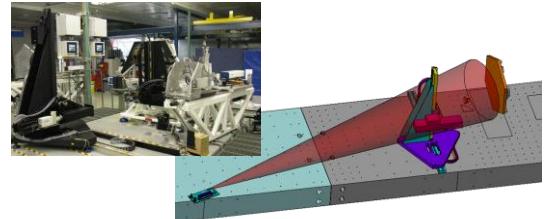
SSHS provided bridge-data between grind and polish, used until

PMSA surface was within capture range of interferometry

SSHS provide mid-spatial frequency control: 222 mm to 2 mm

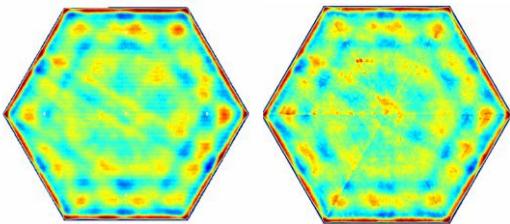
Large dynamic range (0 – 4.6 mrad surface slope)

When not used, convergence rate was degraded.



Comparison (222 - 2 mm spatial periods) 8/1/06

Smooth grind



Point-to-Point Subtraction: SSHS - CMM = 0.27 μm RMS



Rule #4: Know where you are

It might seem simple, but if you don't know where a feature is located on the mirror, you cannot correct it. This requires fiducials.

There are two types of fiducials: Data Fiducials and Distortion Fiducials.

Data fiducials are used to define a coordinate system and locate the measured data in that coordinate system. Sometimes this coordinate system is required to subtract calibration files, other times it is required to produce hit maps.

Distortion fiducials are used to map out test setup pupil distortion.

Many test setups, particularly those with null optics can have radial as well as lateral pupil distortion. Distortion can cause tool mis-registration errors of 10 to 50 mm or more.



Fiducials

Fiducials can be as simple as a piece of tape or ink marks on surface under test or as sophisticated as mechanical 'fingers' protruding into clear aperture.

For computer controlled processes, fiducial positional knowledge is critical.

Because test setups might invert or flip the imaging, I highly recommend an asymmetric pattern. The pattern which I have always used is:
0/180 degree fiducials produce a central axis for the data set,
90 degree fiducial defines left/right, and
30 degree fiducial defines top/bottom.

For rotationally symmetric systems, one option for distortion fiducials is multiple marks along a radius.

But for asymmetric systems, a grid of marks is required.

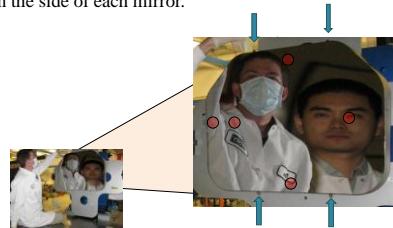
Finally, if you have a clear aperture requirement, place marks inside and outside of the required clear aperture.



Master Datums and Fiducials

Mirrors are manufactured in Observatory Coordinate Space as defined by 'Master Datums' on back of each mirror substrate.

Figure error is measured using 'Data Fiducials' on front of each mirror which are registered to 'Transfer Fiducials' (tooling balls) on the side of each mirror.





Master Datums and Fiducials

Data, Distortion and Edge Fiducials are used for PMSA testing.

Transfer Fiducials register these to the Master Datums on back.

This knowledge is critical because of redundancy between alignment errors and surface figure errors



Lesson Learned

Another problem is software coordinate convention.

Most interferometer analysis software assumes that the optical (Z axis) positive direction points from the surface under test towards the interferometer, such that a feature which is higher than desired is positive.

But, many optical design programs define the positive optical axis to be into the surface.

The problem occurs because both programs will typically define the Y-axis as being up, so it is critical to understand which direction is +X-axis. (I have actually seen a software program which used a left handed coordinate system)

The problem is further complicated when interfacing with the optical shop. You must know the coordinate system of every computer controlled grinding and polishing machine.



Rule #5: 'Test like you fly'

You must 'Test like you fly'.

JWST operates in the cold of space. Therefore, we must certify 30K optical performance in the MSFC XRCF, and 'zero-g' performance via a 6 rotation test at BATC BOTS.

Observatory level qualification < 50K is done at JSC Chamber A.

Also, 'test as you fly' is not limited to space telescopes. Ground based telescopes can have large gravity sags.

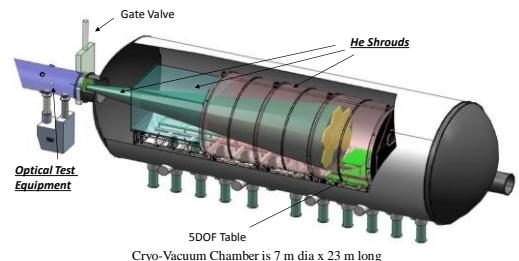
Therefore, they must be tested in their final structure (or a surrogate).



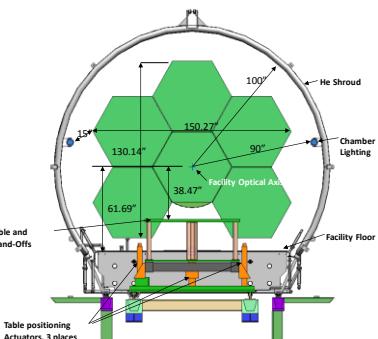
PMSA Flight Mirror Testing at MSFC XRCF

Cryogenic Performance Specifications are Certified at XRCF

Because JWST mirrors are fabricated at room temperature (300K) but operate < 50K, their shape change from 300 K to 30 K is measured to generate a 'hit-map', and cryo-null polish the mirrors.



JWST Flight Mirror Test Configuration

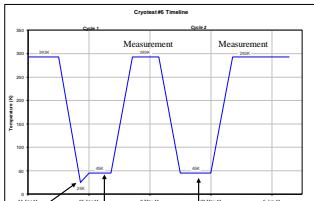
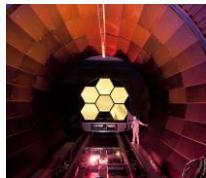


Primary Mirror Cryogenic Tests





XRCF Cryo Test



* Survival Temperature

- Cryo Deployment
- Nominal Measurement
- Hexapod Deformation Pose
- RoC Actuation Test
- Hexapod Pose Test
- Parallel Camera & Redundant Test (3 of 6 PMSAs)
- Set RoC
- Non-Nominal Measurement
- Hexapod Tilt Test
- Parallel Camera & Redundant Test (3 of 6 PMSAs)



Flight Mirrors in XRCF



Lesson Learned

While Gravity is a significant problem for large mirrors.
It is also problem for lightweight mirrors in non-kinematic mounts

Once I had a task to test an 'egg-crate' 0.75 meter diameter flat mirror to 30 nm PV.

After initial characterization tests with the customer, I declined.
The customer provided 'metrology' mount was unsuitable.
The mirror was so 'floppy' (i.e. low stiffness) that simply picking it up and setting it back down onto the metrology mount resulted in a 100 nm PV shape change (both astigmatic bending and local mount stress).



Rule #6: Independent Cross-Checks

Probably the single most 'famous' lesson learned from Hubble is to never rely on a single test to certify a flight specification.

Every JWST optical component specification had a primary certification test and a confirming test.



Every Requirement has an Independent Validation

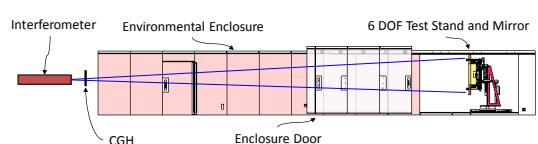
Parameter	Spec	Tol	Units	Verification	Validation
Clear Aperture (Edge Specification)	1.4776 (5)	Mn (Max)	mm²	Measure edges at ambient using Tinsley HS Interferometer	Measure area at cryo using XRCF CoC Interferometer
Scratch-Dig	80-50	Max		Ambient Visual Inspection	Independent Visual
Conic Constant	-0.99966 +/- 0.0005			Measured at cryo and defined by null geometry for XRCF CGH CoC test	Ambient test at Tinsley, compare CGH CoC test with auto-collimation test
Radius of Curvature	*	+/- 0.15	mm	Set at XRCF using ADM	ROCO Comparison
Prescription Alignment Error					
Decenter	*	≤ 0.35	mm	Cryogenic test at XRCF, defined by maximum decenter error relative to CGH CoC test and fiducial alignment	Ambient test at Tinsley, compare CGH CoC test with auto-collimation test
Clocking	0	≤ 0.35	mrad		
Piston	N/A			Ambient CMM measurement at AXSYS	Ambient CMM measurement at Tinsley
Tilt	N/A				
Total Surface Figure Error:					
Low/Mid Frequency	20	Max	nm rms	Cryo-Test at XRCF	Cryo-Test at JSC
High Frequency	7	Max	nm rms		
Surface Roughness	4	Max	nm rms	Ambient Chapman measurement at Tinsley	NONE



Ball Optical Test Station (BOTS)

Tinsley ambient metrology results are 'cross-checked' at BATC BOTS measurements:

- Measure Configuration 1 to 2 deformation
- Measure Configuration 2 to 3 deformation
- Create a Gravity Backout file for use at XRCF
- Measure Vibration Testing Deformation
- Measure Vacuum Bakeout Deformation
- Measure Configuration 2 mirrors for BATC to Tinsley Data Correlation





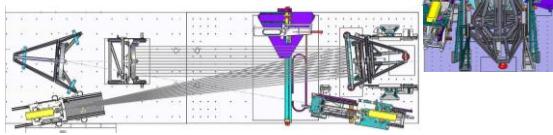
Auto-Collimation Test

Auto-Collimation Test provides independent cross-check of CGH Center of Curvature Test

Verifies:

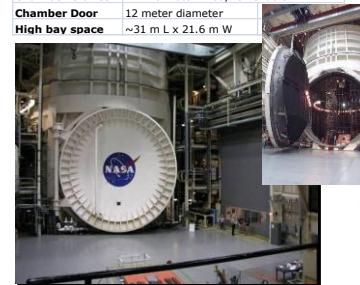
- Radius of Curvature
- Conic Constant
- Off-Axis Distance
- Clocking

Note: is not a full-aperture figure verification test



Final Cross-Check performed at Observatory Level

Johnson Space Center Chamber A	
Chamber size	16.7 meter diameter, 35.6 meter tall
Existing Shrouds	LN2 shroud, GHe panels
Chamber Cranes	4 x 7.6 meter fixed, removable
Chamber Door	12 meter diameter
High bay space	~31 m L x 21.6 m W



Rule #7: Understand All Anomalies

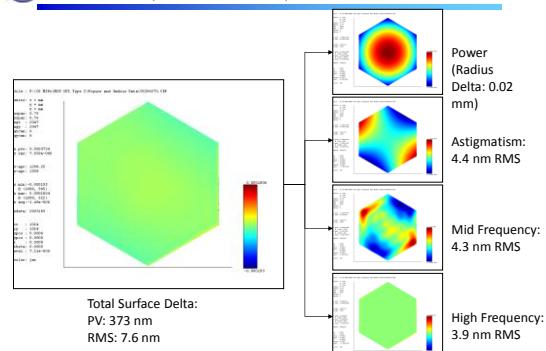
Of all the rules, this one maybe the most important and must be followed with independent rigor.

No matter how small, one must resist the temptation of sweeping a discrepancy under the metaphorical error budget rug.

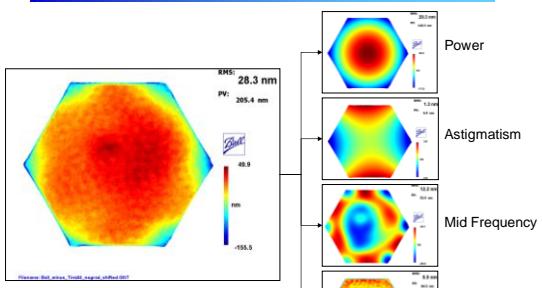


Tinsley Test Reproducibility

(OTS-1 Test #1 vs. Test #2) VC6GA294-VC6HA270



BATC to Tinsley Initial Comparison too large



Initially, BOTS and TOTS Radius did not agree. Discrepancy was determined to be caused by bulk temperature difference. Agreement is now at 10 nm rms level.



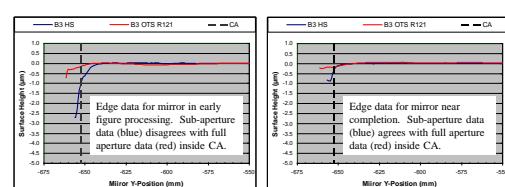
Lesson Learned: Clear Aperture Edge Specification

Center of Curvature test and High-Spatial Frequency test gave entirely different answers for compliance with Edge Requirement – 15 mm difference.

Which one was right had significant cost & schedule impact.

HS was right, CoC was wrong.

Problem was caused by depth of focus and Fresnel diffraction.





Conclusions

Based on 30 years of optical testing experience, I have defined seven guiding principles for optical testing.

- Fully Understand the Task
- Develop an Error Budget
- Continuous Metrology Coverage
- Know where you are
- 'Test like you fly'
- Independent Cross-Checks
- Understand All Anomalies

With maybe an 8th of deliberately disturbing or randomizing the test.

JWST optical component in-process optical testing and cryogenic compliance certification, verification & validation was accomplished by a dedicated metrology team used these principles.

All JWST optical components meet their requirements.